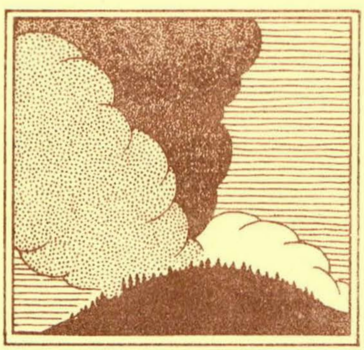
Interim technical Report
AFSWP - 405

THERMAL CONDUCTIVITY OF SOME COMMON FOREST FUELS

Byram



DIVISION OF FIRE RESEARCH
FOREST SERVICE
U. S. DEPARTMENT OF AGRICULTURE

THERMAL CONDUCTIVITY OF SOME COMMON FOREST FUELS

by

G. M. Byram F. M. Sauer
W. L. Fons R. K. Arnold

U. S. Department of Agriculture
Forest Service
Division of Fire Research

A. A. Brown, Division Chief

December 1, 1952

This study is part of a group research project of the Division of Fire Research, Forest Service, U. S. Department of Agriculture, conducted at the California Forest and Range Experiment Station.

ABSTRACT

This study was designed to obtain thermal conductivity of some common forest fuels which hitherto had defied such efforts because of their shape, size, or structure. Dry leaves and decayed wood (punk) were modified so that conductivity measurements could be made by a thin plate uni-directional heat flow calibration stand. Results of these measurements are compatible with a linear relationship between thermal conductivity and specific gravity, established by MacLean, 1/ and indicate that conductivities of most common forest fuels may be determined from their specific gravities. MacLean's equations may be applicable generally to most vegetable fibrous materials.

1/ J. D. MacLean. "Thermal Conductivity of Wood," Heating, Piping, and Air Conditioning, XIII (1941), 380-391.

CONTENTS

ILLUSTRATIONS

TABLES

CHAPTER 1

INTRODUCTION

Studies of ignition and rate of combustion of common forest fuels have been hampered by lack of information concerning thermal conductivity. This gap in basic knowledge is particularly critical in most readily ignitable forest fuels such as thin, dry, or decayed leaves, dry grasses, and decayed wood (punk).

Previous work on wood held promise of being applicable to this problem. From experiments made on thirty-two species of wood in which moisture content was varied from zero (oven-dry) to that in the green condition, MacLean 2/ developed equations for the thermal conductivity of wood, given specific gravity and moisture content:

$$K = \left[(4.78 + 0.097M)S + 0.568\right] \times 10^{-4}; \quad (0 < M < 40) \qquad (1.1)$$

$$K = \left[(4.78 + 0.13M)S + 0.568\right] \times 10^{-4}; \quad (M > 40) \qquad (1.2)$$

where K is thermal conductivity in cal/sec $cm^2(^oC/cm)$; 3/ M is moisture content in per cent based on oven-dry weight; S is specific gravity based on oven-dry weight and wet volume at current moisture content M.

Measurement of thermal conductivity on individual leaves is difficult because of their irregular shape and non-uniform thickness. Difficulties were overcome by breaking the leaves and compressing them into slabs with dimensions appropriate for conductivity measurement equipment.

Punk, on the other hand, is so irregular in structure that it is difficult to obtain uniform specimens with smooth surfaces. Therefore, it was necessary to select solid specimens which were decayed only slightly and to powder and shread highly decayed material.

Specimens actually tested had different specific gravities from the original material, but since results indicated that MacLean's linear relationship between thermal conductivity and specific gravity for wood held for these materials, actual conductivity was computed from measured specific gravity of each specimen.

2/ Ibid.

3/ One cal/sec $cm^2(^oC/cm) = 241.9$ Btu/hr $ft^2(^oF/ft)$.

CHAPTER 2

PROCEDURES

2.1 PREPARATION OF PUNK SPECIMENS

Specimens of Douglas fir and white fir punk were prepared. Douglas fir heartwood punk was fairly hard, brittle, and dark brown in color. Two slabs 4½ in. square and 3/8-in. thick were sawed out and their surfaces sanded. One test slab was cut with its faces perpendicular to the grain, the other with its faces parallel to the grain. A third Douglas fir punk specimen was powdered to obtain a lower value of specific gravity.

White fir sapwood punk tends to fall apart and is usually found in the forest in a finely divided (shredded) state. The white fir sample therefore was tested in its shredded form.

2.2 PREPARATION OF LEAF SPECIMENS

Leaf test slabs 4½ in. square by 3/8-in. thick were formed by placing enough leaf flakes between two chrome-plated steel pressure plates so that the desired thickness and density were obtained when pressure was applied. A dilute solution of casein glue was used as a bonding agent. After pressing to the desired density, the specimen still in the pressure plate unit was placed in an oven at 105° C until the water was driven off.

2.3 THERMAL CONDUCTIVITY MEASUREMENT

Thermal conductivity measurements were made by personnel of the University of California Thermal Radiation Laboratory, using the Thin Plate Uni-directional Heat Flow Calibration Stand. 4/ A detailed description of this calibration apparatus and operation of the heat meters has been published. 5/

4/ A. J. Test, R. V. Dunkle, and J. T. Gier. "Report on Thermal Conductivity of Certain Forest Materials." (Unpublished University of California Institute of Engineering Research Report, Series 39, Issue No. ES5054, August 1951.)

5/ R. V. Dunkle et al. Final Report, Thermal Radiation Project. University of California Institute of Engineering Research, Report Code NR-015-202 (Berkeley, September 1950), Section 10-VII.

For use as a conductivity measuring device, the calibration stand was set up as follows:

Constantan ribbon, .032 x 3/16 in., welded into a heating element, was shellacked to the surface of a heat meter, $4\frac{1}{2}$ x $4\frac{1}{2}$ in. square. The heat meter and heating element were placed on a heating plate which acted as a guard heater. A thin sheet of mica was placed over the heating element for electrical insulation, and aluminum foil placed on top of the mica provided an isothermal surface. A heat meter with three thermocouples affixed to its upper surface was placed on top of the isothermal surface. The specimen to be tested was then placed on top of the meter. Another meter with three thermocouples affixed to its lower surface was placed on top of the specimen and a cooling plate placed on top of the sandwich.

When the temperature of the heating plate equals the temperature of the guard plate, the heat meter between the two heaters indicates zero output. This condition means that the heat from the heater is transferred either to the cooling plate or is lost from the edges. By keeping the temperature of the specimen near to that of the surrounds (approximately 24° C), heat loss to the surrounds from the edges is minimized.

When a steady state was reached, and the heat meter between the two heaters read zero, readings of the two heat meters and the power input to the heater were taken. The average of the two heat-meter readings was used in the calculations. At the same time a different reading was taken of the three thermocouples affixed to each of the meters, giving the temperature drop through the specimen. The average of these readings was used in the calculation.

The specimens were weighed to within .001 lb, the length and width measured to within .01 in., and the thickness to within 0.001 in. All specimens except numbers 7 and 8 were oven dried at a later date to determine moisture content. Moisture content for specimens 7 and 8 was estimated from the prevailing relative humidity at the test station.

CHAPTER 3

RESULTS

Thermal conductivity measurements are summarized in Table 3.1. Each value represents the average of three determinations except for specimen 2 where only two determinations were made. The maximum deviation of any determination from the mean was 5 per cent, while the average deviation was of the order of 2 per cent. Conductivity values were then corrected for moisture content using the results of MacLean 6/ and the specific gravity corrected for shrinkage according to MacLean's Equation 11. 7/ These values corrected to zero per cent moisture (oven-dry) are listed in Table 3.2 and are plotted in Fig. 3.1 along with values computed from Equation 1.1

6/ J. D. MacLean, op. cit., pp. 380-391.

7/ J. D. MacLean. Effect of Moisture Changes on the Shrinking, Swelling, Specific Gravity, Air or Void Space, Weight and Similar Properties of Wood. Forest Products Laboratory Publication No. R1448, Madison, Wisconsin. 1944, p. 18.

TABLE 3.1

Properties and Thermal Conductivities of Fuel Specimens

Specimen	Form Tested	Moisture Content (Per Cent)	Specific Gravity Based on Weight When Oven-dry and Wet Volume at Current Moisture	Thermal Conductivity at Current Moisture (Cal/Sec Cm^2(°C/Cm) x 10^4)
Madrone leaves a/ (*Arbutus menziesii*)	Pressed slab	5.5	0.495	2.97
Do.	Pressed slab	5.2	0.892	4.67
Do.	Pressed slab	4.7	0.604	3.47
Manzanita leaves b/ (*Arctostaphylos patula*)	Pressed slab	6.0	0.940	4.33
Douglas fir punk c/ (*Pseudotsuga taxifolia*)	Slab (perpendicular to grain)	11.6	0.290	2.07
Do.	Slab (parallel to grain)	11.8	0.287	1.82
Do.	Powdered	9.0	0.256	1.92
White fir punk d/ (*Abies concolor*)	Shredded	9.0	0.121	1.53

a/ Freshly fallen leaves.
b/ Old partially-decayed leaves.
c/ Heartwood.
d/ Sapwood.

TABLE 3.2

Specific Gravities and Thermal Conductivities of Materials in Table 3.1, Corrected for Moisture Content

Specimen	Specific Gravity Based on Dry Weight and Dry Volume	Thermal Conductivity at Zero Per Cent Moisture (Cal/Sec Cm^2(^oC/Cm) x 10^4
Madrone leaves	.507	2.71
Madrone leaves	.930	4.24
Madrone leaves	.619	3.20
Manzanita leaves	.992	3.78
Douglas fir punk	.299	1.74
Douglas fir punk	.296	1.49
Douglas fir punk	.261	1.70
White fir punk	.122	1.42

CHAPTER 4

DISCUSSION

Measured conductivity values corrected for moisture content, plotted in Fig. 3.1, are for the most part lower than would be predicted by Equation 1.1. This deviation may be associated with the possible error of surface temperature measurement due to contact resistance between the heat meters and specimen surfaces. The thermocouples used to measure temperature potential were led out between the heat meter surfaces and the specimen surface, thus allowing a small air gap to form. Since the thermocouples were attached to the heat meter surfaces the measured temperature potential would be too large, resulting in a lower than true value of conductivity. If one postulates the thickness of the air film to be twice the diameter of the thermocouple wire used (2 x 0.005 in., for two air gaps), this error in measurement amounts to approximately 25 per cent for the highest specific gravity and 10 per cent for the lowest. Application of this correction would bring the data into juxtaposition with the results of MacLean (Equation 1.1). It was not feasible, however, to determine accurately this correction since the pressure applied to hold the sandwich in place undoubtedly pressed the wires into the specimen somewhat, especially in the softer, less dense materials such as punk slabs and shredded punk.

Correlation between specific gravity and thermal conductivity appears to be sufficiently close for the fuel types tested that the latter may be determined from measurement of the former. It is recommended that Equations 1.1 and 1.2 be used for this purpose due to the abovementioned discrepancy. Table 4.1 gives specific gravities of several different kinds of forest fuels and the corresponding thermal conductivities at zero moisture estimated by Equation 1.1.

The results of MacLean depend upon the fact that at zero specific gravity the conductivity for wood approaches that of air at the average temperature of the wood specimen, which was approximately 30° C for MacLean's data. Calculations concerned with ignition of forest fuels require that thermal conductivity be known up to the charring point (approximately 230° C). Since the conductivity for air increases 50 per cent in this range, 8/ one would expect a proportional increase in the conductivity of fuels of low specific gravity. For this reason a continuation of the present work to include conductivity measurements made at elevated temperature is advisable.

8/ E. R. G. Eckert. Introduction to the Transfer of Heat and Mass. (1st ed.) New York: McGraw-Hill, 1950.

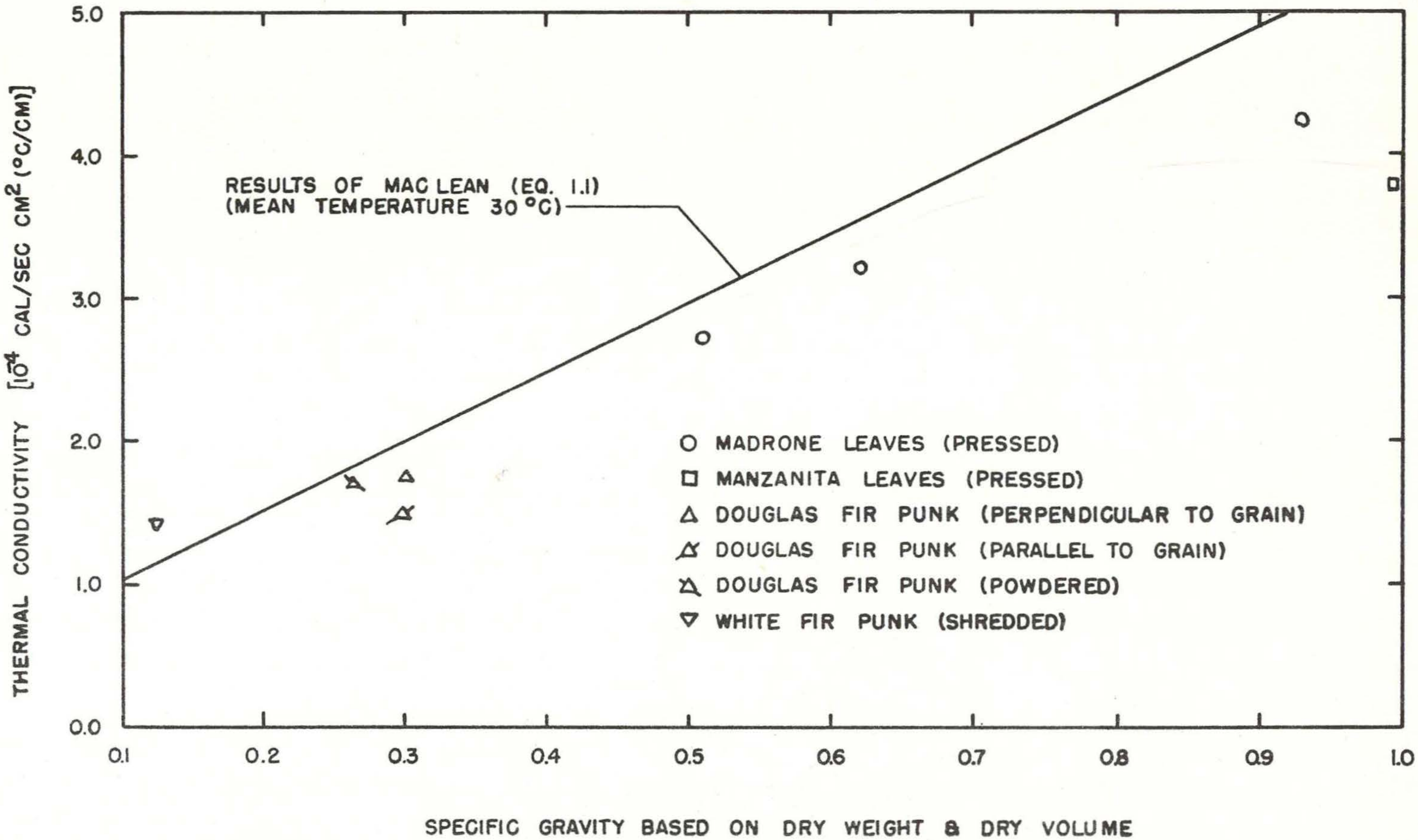


Fig. 3 .1 Thermal Conductivity of Some Common Forest Fuels at Zero Per Cent Moisture

TABLE 4.1

Specific Gravity and Corresponding Thermal Conductivities Estimated by Equation 1.1

Specimen	Specific Gravity, Oven-dry	Estimated Thermal Conductivity, Oven Dry (Cal/Sec $Cm^2(^oC/Cm) \times 10^4$)
Manzanita leaves a/ (*Arctostaphylos patula*)	0.48	2.9
Manzanita leaves b/ (*A. patula*)	0.64	3.6
Madrone leaves b/ (*Arbutus menziesii*)	0.44	2.7
Snowbrush leaves b/ (*Ceanothus velutinus*)	0.57	3.3
Chinquapin leaves b/ (*Castanopsis chrysophylla*)	0.54	3.2
Douglas fir punk (*Pseudotsuga taxifolia*)	0.25	1.8
White fir punk (*Abies concolor*)	0.091-0.14	1.0-1.2
White fir needles (*A. concolor*)	0.55	3.2
Ponderosa pine needles (*Pinus ponderosa*)	0.51	3.0
Lodgepole pine needles (*P. contorta*)	0.57	3.3
Sugar pine needles (*P. lambertiana*)	0.54	3.2

a/ Old partially decayed leaves.

b/ Freshly fallen leaves.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

1. Results of tests indicate that thermal conductivity of forest fuels of known moisture content may be determined from their specific gravity.

2. It is recommended that MacLean's results be used for this purpose in the range of normal atmospheric temperatures.

3. MacLean's equations should be applicable to most vegetable fibrous materials.

4. An extension of the present work to include measurements made at higher temperatures up to the charring point is advisable.